WATER SUPPLY FOR THE CREW DURING SPACEFLIGHTS

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The provision of water for spacecraft crews is one of the more important /389
systems of human life support. The design and construction of a water supply system for the crew in closed confined spaces are dependent in principle on the duration of the flight, the places where the inhabited objects are to function, the properties of cosmic space, and certain other factors. In short expeditions, the crew can best receive its water supply from reserves of drinking water. In this case the normal levels of water consumption are of great importance. However, there are no single normal standards for water consumption by man. According to data in the literature, the volume of drinking water required by a man per day ranges from 1600-2200 ml [11, 12, 13, 18, 20, 22].

A system of water supply based on the use of reserves necessitates the development of ways and means of storing and disinfecting of water. The most effective preservatives of drinking water are coumasin and ionic silver.

In flights lasting several weeks, the need arises for creating an artificial water circulation based on physico-chemical or biological processes.

During the last few years a number of physico-chemical methods have been suggested for regenerating water from human and animal metabolic waste products to supply the crew of spacecraft: distillation under atmospheric pressure, vacuum distillation, extraction, vacuum distillation combined with high-temperature pyrolysis of volatile compounds, a catalytic method under atmospheric and reduced pressures, lyophilization, a method using semipermeable membranes, and so on. Making allowance for the specific conditions on board the spacecraft, and the degree of perfection of water regeneration methods, it seems that the methods of vacuum distillation, lyophilization, the catalytic method, or combinations of these may be capable of practical application.

By means of vacuum distillation at 3 mm Hg and 6-7°, water was obtained which, after additional purification with activated charcoal, satisfied hygienic standards [11].

Welch and co-workers [21] designed a vacuum distillation apparatus which was used in a simulated spacecraft cabin. Two subjects consumed water obtained from human metabolic waste products at a reduced pressure and temperature of 35-37° for a period of 30 days. The water was purified additionally by activated charcoal filters. /390

Investigations showed that the vacuum distillation method can be used without resort to raised temperatures, and since it utilizes the vacuum of cosmic space, this may prove to be a promising method of water regeneration. Disadvantages of this method include the need for an additional purification system based on filters of ion-exchange resins or activated charcoal, because the con-

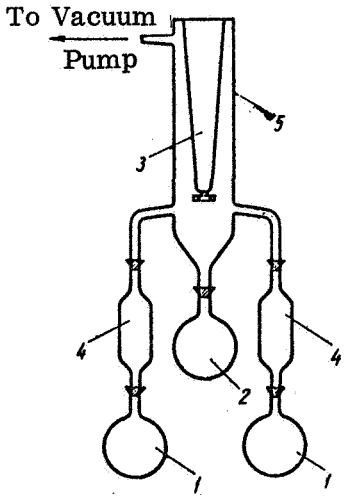

Figure 1. Diagram of Laboratory Apparatus for Water Regeneration by the Lyophilization Method. 1) Vaporizer-Sublimator; 2) Receiver of Regenerated Water; 3) Cryoscopic Mixture; 4) Trap; 5) Condenser-Refrigerator.

densate obtained by vacuum distillation is contaminated with volatile organic substances, ammonia and other compounds. Attempts were naturally made to devise a method free from this disadvantage. One such method is lyophilization. The process of lyophilization is usually carried out in a vacuum of the order of 10^{-3} mm Hg and at reduced evaporation temperatures (sublimation). By making use of differences in the volatilities and molecular weights of substances present in the original product, and the absence of decomposition or formation of new volatile compounds, it is possible to separate comparatively pure water from various food products [4]. However, when the lyophilization method was used to regenerate water from human metabolic waste products, a liquid with unpleasant taste and smell was obtained [19].

Regeneration of water by lyophilization without the need for additional purification was first successfully accomplished by means of a specially designed apparatus. A scheme of a laboratory apparatus for water regeneration from human metabolic waste products by the lyophilization method is shown in Fig. 1.

Water-containing human metabolic waste products are placed in the vaporizer (sublimator). During evacuation of the regeneration system by the vacuum pump, intensive vaporization of the original /391
liquid takes place, and this is accompanied by a sharp fall of temperature. If insufficient heat is supplied to the vaporizer, the solution for regeneration spontaneously freezes. Water vapor and some of the volatile compounds pass into the condenser-refrigerator, where freezing of the moisture and pollutants condensing under these conditions takes place. The uncondensed compounds are evacuated by the pump. Since violent frothing of the original solution is observed in vacuo, traps were used to prevent drops of solution from entering the condenser-refrigerator. After complete extraction of water from the solution, the system is filled with air to atmospheric pressure and the regenerated water formed during thawing of the ice enters the receiver.

The laboratory apparatus described above was used to regenerate water from urine as one of the most highly contaminated sources of water and one of the most difficult to regenerate. Regeneration took place under a vacuum of 10^{-3} mm Hg, measured by a thermocouple vacuum gauge, and the temperature of the condenser-refrigerator was maintained at between -35 and -78° (a cryoscopic mixture of "dry ice" and alcohol). The vaporization temperature varied from -10° to +2°. The results of tests of the lyophilization method for regen- /392
erating water from human urine are given in Table 1.

This table gives a hygienic analysis of the water obtained without additional purification. Water regenerated from urine by lyophilization is a colorless,

transparent liquid with neither odor nor taste. As the table shows, the indices of quality of the water satisfy the demands made on drinking water. Toxicological investigations conducted on batches of rats showed that the regenerated water was perfectly fit for consumption. A characteristic feature of the water obtained is its extremely low content of salts and trace elements. If this water is to be consumed by man for long periods, it must be enriched by appropriate mineral components.

TABLE 1. Results of Hygienic Analysis of Water Regenerated From Human Urine by the Lyophilization Method

Indices of Quality	Magnitude of Index	Allowable Magnitude of Index
pH	6,1—6,3	6,5—8
Transparency, cm	28—30	30
Color, deg	0	20
Oder, points	1—2	2
Oxygen Demands, mg O_2/liter	3—5	2—6
Ammonia Nitrogen, mg/liter	2—3	1
Nitrite Nitrogen, mg/liter	0,003—0,06	0,01
Nitrate Nitrogen, mg/liter	0	2—40
Chlorides, mg/liter	7	200
Phosphates, mg/liter	0,02—0,3	0,1
Sulfates, mg/liter	6—7	20—80
Hardness, mg-eq/liter	0	7
Urea, mg/liter	Traces	0
Uric Acid, mg/liter	0	0
Creatine, mg/liter	0	0
Bacteria Count, $\frac{\text{Number of}}{\text{Bacteria/ml}}$	50—100	100

Commas represent decimal points.

With the lyophilization method as a basis, and utilizing the vacuum of cosmic space and the negative temperatures of the shaded side of the spacecraft, a water regeneration system involving minimal expenditure of energy can be created.

However, the lyophilization method has a number of disadvantages. First, the use of low temperatures for freezing water vapor requires orientation of the

spacecraft, and this is not always possible. Second, if a lyophilization system based on the use of the vacuum of cosmic space is created, allowance must be made for the inevitable loss of uncondensed molecules, for example, of nitrogen, oxygen, carbon dioxide and certain other compounds. In addition, some of the water is lost in proportion to the vapor pressure at the temperatures used.

A method which is free from these disadvantages is one based on the conversion of all volatile toxic strongly smelling and biologically active compounds of organic and inorganic origin into simple oxides or elements. Since these compounds consist mainly of nitrogen, hydrogen, carbon, oxygen and sulfur, their oxidation will produce water, carbon dioxide, and oxides of sulfur and nitrogen. By choosing appropriate conditions of oxidation, elementary nitrogen, water, carbon dioxide and oxides of sulfur can be obtained. The carbon dioxide is readily removed by absorbents in common use. The quantity of sulfur compounds in the volatile and gaseous constituents of the urine, condensate of atmospheric moisture and water used for domestic and hygienic purposes is small, so that the appearance of large concentrations of sulfur oxides in the regenerated water is improbable. Oxides of sulfur can be converted in water into sulfites or sulfates and are then easily removed by ion-exchange resins.

Voltatile compounds of human metabolic waste products can be converted into oxides and elements by various physico-chemical methods: 1) thermal decomposition and oxidation at temperatures of 900-1000° or higher; 2) ozonization; 3) by an oxidative catalytic method; 4) by oxidation in a discharge; 5) by ultrasonic oxidation, and so on. /393

Thermal oxidation requires considerable energy expenditure and, consequently, it can be used only when corresponding supplies of energy are available on board the spacecraft.

Ozonization, which is widely used in the practical deodorization of drinking water [3], is of considerable potential value for regeneration of water from human metabolic waste products. The comparatively high energy expenditure required for ozone production may be provided by the ultraviolet component of the solar spectrum. Oxidation in a discharge and ultrasonic oxidation are still practically undeveloped. At the present time, therefore, the most realistic method of oxidation of volatile compounds is the catalytic method. The literature on complete catalytic oxidation of organic compounds contained in human metabolic waste products is scanty. We know, for example, that methane is oxidized on copper (200°), molybdenum (300°), silver (320°) and vanadium (480°) catalysts [1]. In the presence of the same catalysts, propane, butane and the higher homologs of the aliphatic hydrocarbons are oxidized. It has been shown [6] that acetic acid gives rise to carbon dioxide and water on magnesium-chromium and copper-chromium catalysts; methylethylketone, butyric aldehyde, and ether burn with the formation of a mixture of organic acids.

Extensive investigations have been carried out on the choice of catalysts for oxidation of carbon monoxide into carbon dioxide. Effective catalysts based on oxides of manganese, copper, silver and cobalt [5, 9] and chromite catalysts—oxidizing agents based on silver permanganate [2] have been discovered.

However, the conditions under which oxidative catalysts must work in a water regeneration system are far different from those usually adopted. For example, many catalysts have their activity reduced when working in a humid atmosphere, but in a water regeneration apparatus the relative humidity will be in the region of 100%. Moreover, catalysts very often exhibit marked selectivity with respect to certain classes of compound. In the water regeneration system, however, the catalyst must effectively oxidize all volatile, strongly smelling, toxic and biologically active compounds.

Konikoff and Reynolds [15, 16] have developed a water regeneration system based on high-temperature oxidation of the voltatile compounds of the urine. At 800-1000°, in a reaction zone fitted with a platinum grid under a vacuum of 60 mm Hg, all volatile compounds were destroyed, thus producing water fit for consumption. These workers performed an experiment using human subjects. /394
For six days the subjects drank water regenerated from the urine by the method just described. No effects on the subject were found.

This method is difficult to apply under the actual conditions of space flight, because temperatures of 800-1000° C are difficult to attain (at least during forthcoming flights of short duration).

The present authors have developed a catalytic method of water regeneration from all moisture-containing human metabolic waste products using oxide catalysts. Catalysts prepared on the basis of oxides of certain elements have been shown to work at much lower temperatures [8].

The regeneration system based on the use of oxidative catalytic processes can operate at either atmospheric or reduced pressures. A diagram of such an apparatus is given in Fig. 2.

Water-containing waste products of human and animal metabolism are placed in the receiver-vaporizer. During heating, water vapor and volatile organic compounds enter the catalytic furnace, where they are completely oxidized to nitrogen, water, carbon dioxide and oxides of sulfur. The temperature of the catalytic process is measured by a thermocouple. The vapor passes through the condenser-refrigerator, at a temperature of 10-18°, where it condenses and passes into the pure water receiver, while the uncondensed gases continue through the flow meter and blower. The atmospheric pressure is maintained by a pressure equalizer. The tap 8 is used for taking samples for gas analysis and tap 10 is used when water regeneration is to be carried out under reduced pressure.

The catalytic method was used to regenerate water from urine, condensate /395
of atmospheric moisture, and water used for domestic and hygienic purposes. The relationship between the quality of the regenerated water and the temperature of catalytic oxidation, rate of circulation of air in the closed circuit, quantity of catalyst, nature of the catalytic oxidizing agent, and the geometric parameters of the catalytic reactor was investigated.

Extensive tests were carried out on the regenerated water to determine its hygienic standard. The following methods were used: oxygen demand (perman-

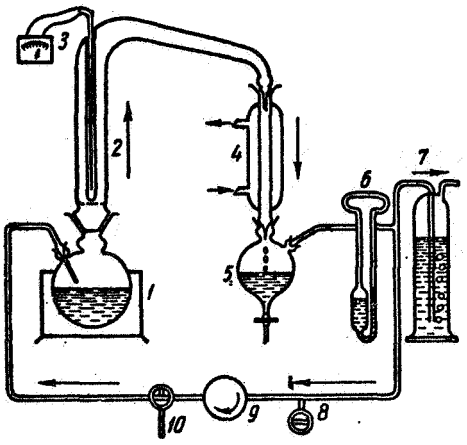

Figure 2. Scheme of Laboratory Apparatus for Water Regeneration by an Oxidative Catalytic Method. 1) Receiver-Vaporizer; 2) Catalytic Reactor; 3) Thermocouple; 4) Condenser-Refrigerator; 5) Receiver of Regenerated Water; 6) Flow Meter; 7) Pressure Equalizer; 8) 2-Way Tap; 9) Blower; 10) 3-Way Tap.

TABLE 2. Results of Hygienic Analysis of Water Obtained From Urine by the Catalytic Method

Tests	Indices of Quality of Regenerated Water	Allowable Indices of Water Quality
Oxygen Demand, mgO_2/liter	1,5	2—6
pH	6,5—7	6,5—8
Transparency, cm	30	30
Color, deg	15	20
Odor, Points	0	2
Ammonia Nitrogen mg/liter	0,1	1
Nitrate Nitrogen, mg/liter	0,1	40
Nitrite Nitrogen, mg/liter	0,02	0,01
Organic Nitrogen, mg/liter	0	0
Sulfates, mg/liter	0—20	80
Chlorides, mg/liter	0	200
Phosphates, mg/liter	0,005	0,1
Hardness, mg-eq/liter	0	7
Ca, mg-eq/liter	0	
Urea, mg/liter	0	0
Uric Acid, mg/liter	0	0
Creatine, mg/liter	0	0
Bacterial Count, No. of Bacteria, mg/l	0	100

ganate and bichromate methods), pH, transparency, color, odor, ammonia nitrogen (colorimetric method using Nessler's reagent), organic nitrogen (Kjeldahl method), nitrate nitrogen (colorimetric method using Griess's reagent), nitrite nitrogen (colorimetric method with disulfophenol indicator), sulfates (complexometric method using Trilon B indicator), chlorides (Mohr's method), phosphates (by Denny's ceruliomolybdate method), hardness and calcium (complexometric method using Trilon B indicator), urea (Borodin's method), creatinine (Folin's method), uric acid, and also the number of colonies of Escherichia coli /396 (bacterial count).

The results of hygienic analysis of water obtained from urine by the catalytic method are given in Table 2. These results were obtained for water regenerated under the following conditions: temperature of catalyst 150°, rate of circulation 4-5 liters/min, temperature of condenser 18°, temperature of vaporization of original product 50°. The pressure of the vapor and air medium in the circulation system was atmospheric. Water regeneration took place on a catalyst prepared on the basis of manganese oxides.

Water obtained from human urine by the catalytic method is a colorless, transparent liquid with neither smell nor taste. The oxygen demand of the water (volume of oxygen required to oxidize organic contaminants), which is 1-5 mg O_2/liter, and also the absence of organic nitrogen, demonstrate that mineralization of the organic constituents of the urine is practically complete. As Table 2 shows, this water without further purification satisfies the hygiene standards of drinking water.

The quality of the water is highly dependent on the vaporization temperature of the original solution. Whereas the water obtained at a temperature of 50° fully satisfies the hygienic standards, at a temperature of 100° or above, slightly higher concentrations of ammonia and nitrites are observed, but these are readily absorbed by ion-exchange resins. The increase in ammonia concentration depending on vaporization temperature of the original solution may be attributed to an increase in the rate of decomposition of urea, hydrolysis of which is accompanied by the formation of ammonia and carbon dioxide. At 50° the degree of decomposition of urea is slight; if, however, water regeneration takes place at higher temperatures, the rate of urea decomposition rises, and most of the ammonium is set free after removal of a certain volume of water from the original solution. The quantity of ammonia in regenerated water as a function of the degree of extraction of water from the urine is shown in Fig. 3.

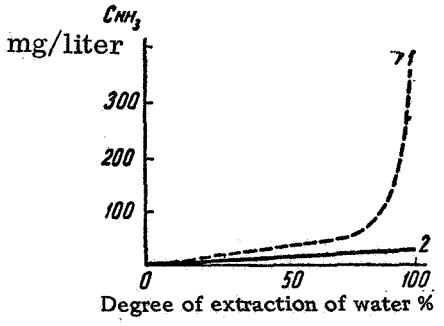

Figure 3. Changes in Ammonia Concentration in Distillate Depending on Degree of Extraction of Water From Urine. 1) Ammonia Concentration in Distillate with Catalytic Reactor not Working; 2) Ammonia Concentration with Reactor Working.

Curve 1 in Fig. 3 was obtained for a circulation apparatus when the vaporization temperature of the original product is 100°. In this case the catalyst in the reactor is uncharged. Curve 2 corresponds to the increase in ammonia depending on the degree of water extraction with the catalytic reactor working. It is clear from Fig. 3 that up to 80-90% of water extraction, the distillate contains a negligible quantity of ammonia, but thereafter a sharp increase is observed in its concentration. The sharp rise in ammonia is evidently due to an increase in the rate of decomposition of urea by the action of catalytic salts, whose catalytic action begins to be exhibited distinctly only at high concentrations of solid residue of the urine.

The quality of the regenerated water and productivity of the apparatus are influenced by the barometric pressure in the circulation system. A reduced pressure of 360 mm Hg created by a blower makes it possible to obtain drinking /397
water for a long period, without the use of an additional purification system, with a considerably increased output of the regeneration system. A distinguishing feature of the work of the apparatus at reduced pressures is a sharp decrease in the formation of gaseous products.

These investigations showed that catalytic system prepared on the basis of oxides of chromium, nickel and manganese may be used as catalytic oxidizing agents for water regneration from human urine.

In the limited room available in the spacecraft cabin, a considerable proportion of waste products is accounted for by condensate of atmospheric moisture (1000-1200 ml/day per person) and by water used for domestic and hygienic purposes (1800-2000 ml). Regeneration of water from these sources is a task of no less complexity, despite the fact that the concentration of contaminants in the condensate and domestic water is much lower than in the urine. The difficulty in creating a reliable method of regenerating water from condensate of atmospheric moisture is the complexity and indefiniteness of its chemical composition. The condensate may contain secretions of the sweat and sebaceous glands, composed of fatty acids and their esters, proteins, urea and creatinine. The condensate is contaminated by volatile substances found in the urine and feces (amines, ammonia, mercaptans, hydrogen sulfide). Voltatile components of covering materials, substances formed as a result of operation of equipment and instruments on board the spacecraft, and volatile compounds present in mixtures used for hygienic and disinfecting purposes make additional difficulties in the work of developing a method of water regneration. Chemical analysis of the condensate obtained in one chamber showed that it contained the following contaminants: ketones, aldehydes, alcohols, amino-compounds, ammonia, and other compounds.

The chemical composition of the condensate as described above refers only to the particular conditions under which it was collected. If the environmental conditions in the spacecraft cabin are changed, the chemical composition of the /398
condensate will naturally be different. Consequently, when developing a system of regenerating water from condensate of atmospheric moisture, the universality of the selected methods is important. From the energetic point of view, it is naturally convenient to regenerate water from condensate of atmospheric moisture by means of adsorbents and ion-exchange resins. However, it is an extremely difficult problem to create an adsorbent for a medium of indefinite and extremely varied chemical composition. The most acceptable solution to

the problem of developing a system of water regeneration from the condensate of atmospheric moisture is the method of oxidation of all volatile organic compounds. For this purpose we have used the method of catalytic oxidation based on the design of the laboratory regeneration apparatus described above. The conditions for water regeneration from condensate of atmospheric moisture and water used for domestic and hygienic purposes were as follows: 1) temperature of catalytic furnace 150°, 2) temperature of condenser 15-18°, 3) air circulation rate 4-5 liters/h. The results of these investigations are summarized in Table 3.

TABLE 3. Chemical Composition of Water Obtained from Condensate of Atmospheric Moisture and Water Used for Hygienic and Domestic Purposes

Indices of Quality	Magnitude of Indices of Quality for Water Regenerated from		Allowable Indices for Drinking Water
	Condensate of Atmospheric Moisture	Hygienic and Domestic Water	
Oxygen Demand, mg O_2/liter	1—2	1—3	2—6
pH	6,5	6,5	6,5—8
Transparency, cm	30	30	30
Color, deg	10	10	20
Odor, Points	0	0	2
Ammonia Nitrogen, mg/liter	0	3,7	1
Nitrate Nitrogen, mg/liter	0,01	0,3	40
Nitrate Nitrogen, mg/liter	0,01	0,1	0,1
Organic Nitrogen, mg/liter	0	0	0
Sulfates, mg/liter	0	—	80
Chlorides, mg/liter	0	—	200
Phosphates, mg/liter	0	—	0,1
Hardness, mg-eq/liter	0	0	7
Calcium, mg-eq/liter	0	0	—
Urea, mg/liter	0	0	0
Uric Acid, mg/liter	0	0	0
Creatine, mg/liter	0	0	0
Alcohols, mg/liter	0	0	0
Aldehydes, mg/liter	0	0	0

Commas represent decimal points.

Water obtained by the catalytic oxidation method from condensate of atmospheric moisture and hygienic and domestic water is a transparent liquid with no taste or smell. The indices of water quality satisfy the standards for drinking water.

However, it must be remembered that to give the regenerated water its customary taste qualities, hardness giving salts and trace elements must be added.

From repeated hygienic analyses of the regenerated water, it was concluded that it is suitable for drinking. This conclusion was confirmed experimentally in investigations of laboratory animals (rats). For three months the rats drank water regenerated from human urine.

These investigations showed that the regenerated water has no toxic action on rats.

Analysis of the results of combined hygienic, bacteriologic and toxicologic investigations indicated that experiments could safely be carried out on man.

The possibility of consuming water regenerated by the catalytic method was tested on three human subjects for 30 days. Clinical and physiological tests were performed on the subjects before, during and after the experiment. The water metabolism, cardiovascular and respiratory systems, and hematologic and biochemical indices were investigated. As a result of these investigations it was concluded that water regenerated from urine by the catalytic method is /399
fit for human consumption as drinking water. The human subjects taking part in the experiment showed no pathological changes or manifestations of toxicoses.

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